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LASER DOPPLER VELOCIMETER MEASUREMENTS IN A TURBULENT JET EXITING INTO A CROSS FLOW

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NOTICES

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FOREWORD

The work reported herein was sponsored by the Air Force Flight Dynamics Laboratory, Air Force Systems Command (AFSC), under Program Element 64207F, Project 69BT. The work was monitored and supported by the Arnold Engineering Development Center (AEDC) under Contract F40600-70-C-0005. Project monitor was Capt. Carlos Tirres, Directorate of Technology, AEDC.

The effort was conducted from June 1970 to June 1971 at the Mechanical Engineering Laboratory, Oklahoma State University. The manuscript was submitted for publication in October 1971.

Contributing to the effort, in addition to the author were: Professor L. J. Fila, Mr. G. L. Donohue, Mr. P. J. Wallen, and Mr. M. M. Reischman of the School of Mechanical and Aerospace Engineering, Oklahoma State University.

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This technical report has been reviewed and is approved.

Carlos Tirres
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ABSTRACT

Measurements were made of horizontal and vertical velocity components along the center line plane of a turbulent jet exiting into a cross flow. The dual scatter laser Doppler velocimeter was used in both the continuous wave mode and the individual realization mode. In the latter case, numerical averaging over many individual measurements was used to compute the average velocity components. Encouraging results were obtained which indicate that the laser Doppler velocimeter will become an important tool in the field of experimental fluid mechanics.

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SECTION I

INTRODUCTION

The primary objectives of this research were twofold. The first was to measure the velocities in the flowfield near a turbulent jet exiting into a cross flow. A second objective was to use the laser Doppler velocimeter to perform the measurements and hence establish some experience with the new experimeter's tool, especially in the wind tunnel environment.

The flowfield of a jet exiting into a cross flow is of current interest with consideration being given to new configurations of vertical takeoff aircraft. Such configurations obtain initial lift on takeoff from jets, deflected downward from the wings. With the onset of forward motion there is generally a considerable loss in lift from the in-wing jets. In an effort to understand this phenomena more thoroughly, one objective of this research was to supply much needed experimental evidence of the flowfield.

There is a dearth of good experimental evidence on the flowfield of deflected jets at the present time. This has no doubt hampered theoretical efforts which have not made much progress since the work of Abramovich (1). Complete flowfield measurements of the deflected jet are considerably difficult because of the drastically changing flow directions. Mosher (2) has recently completed a very extensive flowfield survey for a ratio of jet velocity to free stream velocity (λ) of 8.

He has carefully measured flow directions at most places and aligned his pitot and static probes to give quite accurate measurements from which he calculates velocity. In addition he has made extensive flow visualization studies and plate surface measurements. However, he is inherently limited, in using conventional probes, to staying away from the recirculating flow region immediately behind the jet near the plate surface. There is little hope that conventional probes would ever be successful in measuring the velocities in that flow region.

It is in flow situations such as the one described above, that the laser Doppler velocimeter (LDV) will play a major role. The LDV offers tremendous promise as the measurement system to be used in flow situations in which placing a conventional probe (such as a pressure probe or a hot wire) either is inconvenient or noticeably disturbs the existing flow. The interference of the LDV beams is negligible, since the energy added to the air is many orders of magnitude less than the kinetic energy of the moving air.

The LDV is a relatively new measurement system which only recently has been used in wind tunnels (References (3) (4) and (5)). The principle has been proven a number of times in very controlled flow situations, particularly where the velocimeter optics is aligned once and not moved again. Less controlled flow situations such as the deflected jet in the wind tunnel introduce practical difficulties associated

with alignment, traversing and seeding. The laser Doppler velocimeter actually measures the velocity of particles of dust, vapor, or smoke known as "seed" either naturally present or artificially placed in the flow. In order to reliably infer the velocity of the air containing the seed the assumption must be made that the seed travels with the air at all times. In many cases this is a very good assumption but there are circumstances when there is considerable inaccuracy introduced because of the particle slip. It is apparent that the problems associated with seeding the air are minimal in most controlled flow situations in which extensive laser velocimeter measurements have been performed. It is also apparent that it is in the wind tunnel applications that the seeding problems are going to be significant. The work of Yanta et. al. (5), discusses this problem to some extent. As a result of the present state of the art of LDV technology and its tremendous promise for the future, the second objective of this research was to build up more experience with the LDV in the wind tunnel environment.

The experiments in this program were all performed with a jet velocity equal to four times the free stream velocity (λ = 4). This figure was chosen since this jet would easily fit our small (16 X 16 in. cross section) wind tunnel and the resulting velocities could be maintained low enough to have Doppler frequencies within the capabilities of our electronic systems. The choice of λ = 4 also filled a gap in existing data, as the only extensive flowfield measurements,

made by Mosher (2) were performed at $\lambda = 8$. The jet exit was circular in cross section, the configuration for which most theoretical and experimental work has been done.

The LDV built in our laboratory was capable of measuring the horizontal and vertical velocity components (not the transverse or y component). However, all velocities were measured along the jet centerline (y = 0) where, by symmetry, the transverse velocity component was zero.

SECTION II

EXPERIMENTAL PROCEDURES

2.1 Wind Tunnel and Model

The wind tunnel used was the Oklahoma State University, Mechanical Engineering Laboratory low speed wind tunnel. This is an open return tunnel with a test section 16 in. square. The fan is a centrifugal blower driven by a constant speed electric motor. Tunnel speed control is accomplished by a set of control vanes at the inlet to the blower. It was desired to reduce the tunnel velocity as low as possible (to 9.3 ft/sec with a corresponding jet velocity of 37.2 ft/sec) since this would yield Doppler frequencies which were more compatible with the electronic capabilities of our system. For this reason 2 inch foam was added to the inlet of the tunnel to decrease the tunnel velocity to the 9.3 ft/sec. However, only a limited number of measurements were made under these conditions because the foam filtered out most of the dust and hence most of the scatter centers for the LDV. The bulk of the measurements were made without foam on the inlet with a tunnel velocity of 15 ft/sec and a jet velocity of 60 ft/sec. (nominal).

A sketch of the splitter plate and jet is shown in Figure 1, with the coordinate system used in the program (the y coordinate is out of the paper). The contraction section for the jet was actually in two stages

with the initial contraction from the stilling chamber outside the tunnel some 6 inches ahead of the jet exit. A final 4 to 1 area contraction was constructed just at the jet exit, whose final diameter was 0.414 in. An F and P precision bore flow meter was used to measure the jet flow, and maintain the desired jet velocity to yield $\lambda = 4$. The tunnel free stream velocity was monitored with a pitot-static probe mounted ahead and below the measurement region. The pitot-static pressure was read with a Trimount micro-manometer accurate to ± 1%. The jet flow measurement was accurate to approximately ± 2%. The jet exit velocity was calculated from the mass flow and area, and was also measured with a standard pitot probe as an additional check on the flow meter.

2.2 Laser Doppler Velocimeter

The electro-optical systems presently used by LDV's fall into two main categories. The first is known as the reference beam system initially proposed by Yeh and Cummins (6). In this system the scattered light from one beam is optically heterodyned with light from a reference beam. The beat frequency, sensed by the photodetector, is the Doppler shift frequency of the scattered light.

The second category of LDV's, first proposed by Rudd (7), and widely adopted by other investigators (4), is known as the dual scatter system. With this system there is no reference beam, but instead scattered light from two separate (but spacially and temporally coherent)

beams is optically heterodyned. In the dual scatter system much more light can be focused on the photodetector without any of the frequency broadening prevalent in the reference beam system. As a result there is generally a higher signal to noise ratio using the newer system.

There is another important feature of the dual scatter LDV system which is important in this research. The light entering the photodetector is all scattered light, the two sources of which are almost the same amplitude. For this reason efficient heterodyning occurs for all size scatter centers. If the receiving electronics has the capability of handling signals of a wide range of amplitudes then the system will measure the velocity of all size scatter centers down to the small smoke particles. With the reference beam system, the amplitude of the reference beam is set to a convenient amplitude and efficient heterodyning occurs only when the light scattered from the scatter centers which enters the photodetector is of approximately the same amplitude as the reference beam. Since the amount of scattered light is a strong function of the size of the scatter center, the reference beam system is essentially set to measure the Doppler frequency shift of one size particle. When a much larger particle enters the probe volume it scatters much more light which then dominates the reference beam. As a result there is no heterodyning and the photodetector simply registers a large dc excursion. This phenomena does not occur when using the dual scatter system - and for this reason the latter system is much more convenient when an uncontrolled, natural seed is being used for scatter centers.

As pointed out by Lennert, et. al. (4) the information coming to the photodetector in the dual scatter system consists of independent bursts with a Doppler frequency superposed upon it. (In the continuous wave (CW) operation the bursts come close enough together in time to give a continuous signal.) The Doppler frequency is proportional to the velocity of the scatter center which, in many cases, is identical to the velocity of the fluid at that point in space and time. In a steady laminar flow situation this velocity will be constant with time and hence only one measurement is necessary to obtain the velocity at that point, (or more exactly that particular component of the velocity).

The flowfield being investigated in this research is a turbulent flow and hence time dependent. In most prior investigations of average velocity in a turbulent flow the average measurement was obtained directly by electronically measuring the average Doppler frequency. This type of measurement requires continuous wave operation which requires the continuous introduction of smoke, into the flowfield. Introduction of the quantities of smoke necessary for wind tunnel work is a considerable problem in itself. The individual realization LDV system operating with natural seed offers a good alternative that avoids the smoke seeding problem.

Ordinary wave analysers or spectrum analysers cannot measure the Doppler frequency on short bursts of information with less than 50

cycles of Doppler frequency in a burst. We have devised a scheme using a Tektronics 535A oscilloscope and a Beckman Model 7360 counter which electronically counts the number of cycles in the sweep time of the oscilloscope. A schematic of this data acquistion system is shown in Figure 2.

The procedure used during wind tunnel runs was to set the measurement point and check the tunnel and jet flow conditions, and then simply record a number of counter readings which represent individual velocity measurements. Between 20 and 60 readings would be taken at each point, and usually the counter readings would be taken at two different sweep settings.

This system for measuring average velocity, in principle, can be extended to obtain the root mean square fluctuating velocity components. However, before this can be accomplished, the data acquisition system must be more automated.

2.2.1 LDV Optics System

The optics system used with our LDV is a new design recently pioneered by Sullivan and shown in Figure 3. This optics package is a variation on the self aligning optics package of Brayton (8). Its major advantage is that it is constructed of a low cost beam splitter, however it has some subsidiary advantages. For example, the beams are split with equal path lengths minimizing the number of free surfaces and their associated reflection losses. It is convenient to adjust

for equal intensities of the two split beams simply by adjusting the polarization orientation of the incoming beam. The optical system was designed so that a simple rotation of the optics could be performed to change from the vertical to the horizontal velocity component measurement. The beam splitting used in this design is particularly suitable to extend the design to simultaneous measurement of two components of velocity. In fact the compactness makes the design attractive if backscattering is to be measured to obtain simultaneous measurement of three components of velocity.

The angle between the two scattering beams in our optics package was a very shallow 2.7°. This led to an undesirably long scattering volume which, using the criteria set down by Goethert (9), is about .300 inches. It is obvious that this poor spacial resolution can be a major source of experimental error. In principle, the source is easy to remove by steepening the beam angle or by increasing the jet size. However, steeper beam angles raise the Doppler frequency in direct proportion. Since we were pushing the upper frequency bounds of our data acquisition electronics we could not raise the frequency without considerable expense in new electronic components (the impedance isolation amplifiers and counter were limited to frequencies below 2 MHz). For this reason the poor spacial resolution was tolerated for these measurements.

2.3 Seed Generation

For the individual realization mode of operation of the LDV microscopic dust naturally present in the laboratory air provided plentiful seed for measurements in the free stream of the wind tunnel. When foam was placed on the tunnel inlet, it filtered most of the dust out and hence had to be removed. No attempt was made to seed the mean stream with smoke (for CW operation) since the tunnel had an open return and any large amount of smoking proved too bothersome to the wind tunnel test crew.

The jet itself had almost no dust present in it due to filtering of the air supply at the compressor. To seed the jet air, a smoke generator was used which essentially was kerosene dripping onto a hot plate. This device provided an abundance of small smoke particles for CW operation as well as a reasonable number of coalesced smoke or kerosene droplets that were large enough for the individual realization mode of operation.

2.4 Uncertainty in Velocity Measurement

The uncertainties in velocity measurement with the LDV are similar to those outlined by Smith and Parsons (3). In order of importance (in our experiment) these sources of error are:

1) Inability of the seed particles to follow the fluid.

2) Finite size of the probe volume.

3) Systematic error introduced in the frequency measurement.

4) Error in locating the focal volume in the flow.

5) Error in measuring beam intersection angle.

6) Random error due to ± 1 count of the electronic counter.

The number one source of systematic error is the inability of the seed particle to follow the fluid. Associated with this error is the error caused by a nonuniform seed density throughout the fluid (the free stream air has many more scatter centers than does the jet air). For instance, in individual realization operation if no seed were added to the jet then almost all the Doppler signals received would come from scatter centers originally in the mean stream. This would introduce a bias into the statistical averaging of the turbulent mixing region and lead to incorrect results. Hence, for individual realization operation it was desired to seed the jet with approximately the same uniformity as the free stream. However, there is uncertainty in how much seed we were actually adding and as a result this could be a source of measurement uncertainty. More important, it appears that the coalesced smoke particles were actually too large such that slip occurred between them and the jet air. This point is demonstrated in the section on Experimental Results.

The probe volume, both computed by the method of Goethert (9) and determined experimentally by traversing a rotating hair, is approximately 0.3 in. long. This is seven tenths of a jet diameter which is very poor resolution. It is difficult to put a numerical value on the uncertainty caused by this spacial averaging, but it is obvious that

the error introduced will be greatest near the jet exit and will diminish as the probe is moved away from the exit where the jet has expanded.

The systematic error introduced by the frequency measurement can be minimized by either improved electronics or by careful application of the existing electronics. There are two ways in which the operator of the LDV can reduce the frequency measurement error. First, he must make sure that the bandpass filter is properly set so that he is not cutting off any of the measurements. Secondly, he must watch the oscilloscope and make a judgement that the Doppler signal was of sufficient amplitude to trigger the counter on each cycle. (In other words, make sure the counter measures the correct frequency.) By looking at the shape of the burst of information the LDV operator can effectively reduce the size of the probe volume by judging which particles are going through the center, and which are going through the edges of the probe volume, and not recording the latter. The different signals shapes, as related to the location in the probe volume, is discussed thoroughly in Lennert, et. al. (4).

In the present experiment the uncertainty in locating the probe was of the order of ± .050 in. Greater operator care could reduce this figure significantly. The measurement of the beam intersection angle proved to introduce comparatively negligible error since it was checked with accurate calibration of the velocity of a hair on a rotating disc.

The last listed error, associated with the ± 1 count of the electronic counter introduced negligible error since it is random in nature, and since many more than ten readings were taken to compute the average frequency, the error would average to zero.

SECTION III

EXPERIMENTAL RESULTS

Table 1 presents actual individual realization raw data obtained at the measurement location $z/d = 3$, $y = 0$ and $x = -.050$ in. $= -.121$ d. There is a $\pm$ 1 count random uncertainty in each realization, however, averaging over more than 10 readings reduces this uncertainty to be negligible. The systematic uncertainty in the average velocity is a strong function of measurement location as discussed in the prior section.

Figure 4 presents average vertical velocity component measurements at 1, 3, and 5 jet diameters from the plate surface. The solid symbols represent the measurements made in the CW mode of operation. The peak velocity predicted by the CW operation is almost exactly equal to the jet exit velocity, which you would expect, only one jet diameter from the exit. The consistent 10% discrepency between the CW and individual realization modes was clearly caused by particle slip in the latter case. This slip is a consequence of the secondary contraction at the jet exit which produces an acceleration that the large particles cannot sustain.

At this location, in the individual realization operation, some of the largest amplitude burst signals (which come from large particle scattered light) were of the lowest frequency which substantiates the explanation of particle slip. Because of the obvious assignable cause of the slip error, the CW measurements, which use the small particle

Table 1. Raw Data From Measurement of Vertical Velocity Component at $z/d = 3$, $y = 0$, $x/d = -.121d$.

Scope Sweep Rate	Counts Per Sweep	Scope Sweep Rate	Counts Per Sweep
2μsec/cm	18	1μsec/cm	7
	20		8
(sweep time	17	(sweep time	9
= 18.60 μsec)	16	= 9.30 μsec)	10
	18		9
	17		9
	20		7
	20		10
	17		9
	15		9
	16		9
	18		10
	16		10
	18		9
	16		10
	ave count = 17.24		10
			ave count = 9.06

$$f_{ave} = \frac{17.24}{18.60 \times 10^{-6}} = 927 \text{ KHz}$$

$$V_{zave} = 42.61 \text{ ft/sec}$$

$$V_{zave}/V_{\infty} = 2.86$$

(46.48 ft/sec ≡ 1 MHz)

$$f_{ave} = \frac{9.06}{9.30 \times 10^{-6}} = 974 \text{ KHz}$$

$$V_{zave} = 44.70 \text{ ft/sec}$$

$$V_{zave}/V_{\infty} = 3.00$$

$$V_{\infty} = 14.9 \text{ ft/sec}$$

smoke seed, were taken as representing the actual velocity. No CW measurements were possible outside the jet or at z locations greater than 1 diameter. At the larger z locations there is substantial mixing with the free stream which had no smoke additive and hense no "continuous" seed. As a result signal drop off was so frequent as to make CW measurements unreliable.

In this investigation, the individual realization measurements using natural seed are much more complete due to the smoke seeding problem. The spread in the data indicates that the repeatability of the measurement system in this application is of the order of ± 10% where the turbulent intensity is not too large. In the wake, the turbulent intensity is much larger and mainly because of electronic limitations and large probe volume size the repeatability is not as good. Because velocities and accelerations are smaller in the wake, it is not expected that particle slip causes significant error in this flow region. Similarly, at z locations of 3 and 5 it is not expected that particle slip is important.

A limited number of tests were run at the lower free stream velocity of 9.3 ft/sec. The fact that these measurements are in reasonable agreement with the data taken with V_∞ = 15 ft/sec indicates that any systematic error introduced by the frequency counting electronics is not significant. More tests were not performed at the lower tunnel velocity because the foam used on the inlet of the tunnel

to reduce the tunnel velocity proved to be too good a filter and filtered most of the dust particles out of the air. Hence, there was a scarcity of scatter centers for the LDV.

In the mean stream, since accelerations are negligible, the scatter centers are travelling with the fluid (no slip). In addition, the large probe volume causes no inaccuracy since the flow is uniform. With the two major sources of systematic error no longer a problem, we would expect to measure the velocity accurately, and in fact the measurements of the horizontal velocity component bears this out. (See Figure 5) The streamwise velocity measured at the smallest x location at $z/d = 5$ is within 2% of the measured free stream velocity. Similar results were obtained when the jet was turned off and the LDV was calibrated against the wind tunnel pitot-static probe.

The behavior of the x velocity component is very reasonable. Up near the jet exit the x velocity behaves similarly to that of flow around a solid circular cylinder. Notably there is an initial decrease in the velocity upon approaching the jet, and in the separated wake region the x velocities are less than free stream, returning asymptotically to the free stream value with increasing downstream coordinate.

At the vertical location $z/d = 1$ some measurements of horizontal velocity component were unreliable. When there is a very large z velocity component (like ten or twenty times the x velocity component) the measurement of the x velocity becomes very difficult. This is

because scatter centers spend such a short time in the scatter volume so as to yield only a few "Doppler" cycles. The CW operation did not yield any signal for x velocity in the middle of the jet at $z/d = 1$. Indications are that this is a problem inherent in LDV measurements.

The vertical velocity measurements are perhaps more indicative of the flow structure than are the horizontal velocity measurements. From the almost immediate distortion of the originally flat and symmetrical velocity profile one can see that the leading edge of the jet is flattening considerably. In the near wake of the jet there are quite large vertical velocity components indicating substantial mixing between the jet air and the mean stream air. In fact what could be defined as a trailing mixing layer is very much thicker and continues to grow much thicker than the leading edge mixing layer. The net result is that the jet thickens considerably. This tells nothing of the distortion of the circular jet to a kidney shape which is predicted by inviscid theory (Abramovich) (1). Measurements off the axis would be necessary to clarify that structure.

Careful examination of the vertical velocity measurements at $z/d = 1$ and 3 shows a second maximum in velocity downstream of the initial major maximum associated with the main jet flow. This second maximum indicates the presence immediately behind the jet, and close to the plate, of a recirculating flow region. Mosher's (2) oil slick tests indicated the extent of this recirculating to be

approximately one jet diameter, and the present measurements are consistent with his. In fact, because the LDV does not disturb the flow, it is in this area of the flowfield that more extensive measurements with the LDV would prove very valuable.

More reliability in the measurements is indicated when the two velocity components are combined to find an actual velocity magnitude and a flow direction. These velocity profiles, together with their directions are plotted on a composite in Figure 6. Notice that the vectors for the most part line up with reasonable average streamlines which define a jet path very similar to those measured by Mosher (2) and by Margason (10).

SECTION IV

CONCLUSIONS

Vertical and streamwise velocity component measurements were made in the flowfield of the deflected jet. Most indications are that these measurements are reasonably accurate over most of the flowfield. It has been demonstrated that with state of the art laser Doppler velocimeter technology, it is an ideal measurement system to determine the complete flowfield of the deflected jet. In addition, the use of the individual realization operation of the LDV in a turbulent flow situation has been reduced to practice. Indications are that this system will play an important role in future experiments in fluid turbulence.

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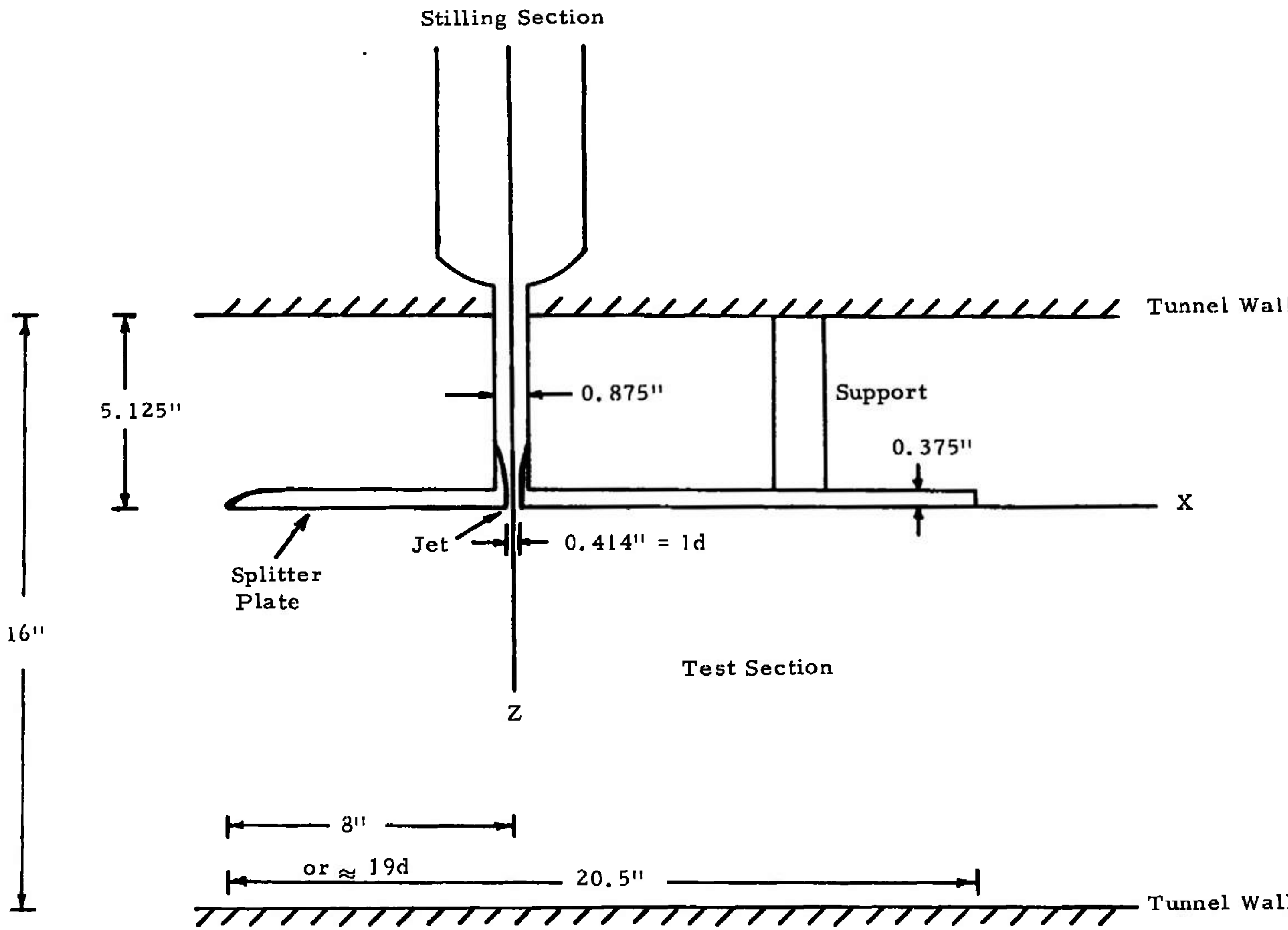

Figure 1: Splitter Plate and Jet

Data Acquisition System

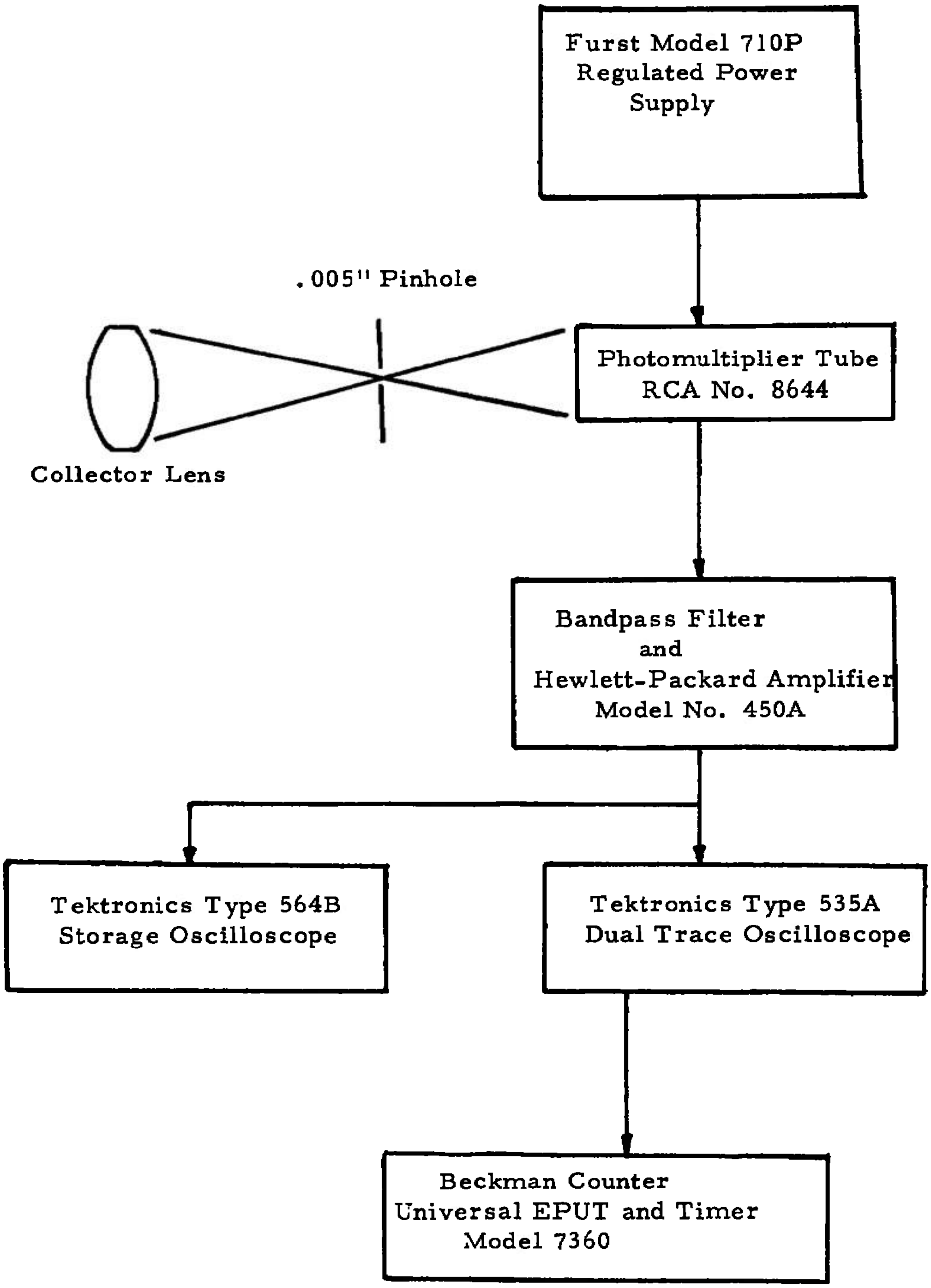

Figure 2: Data Acquisition System

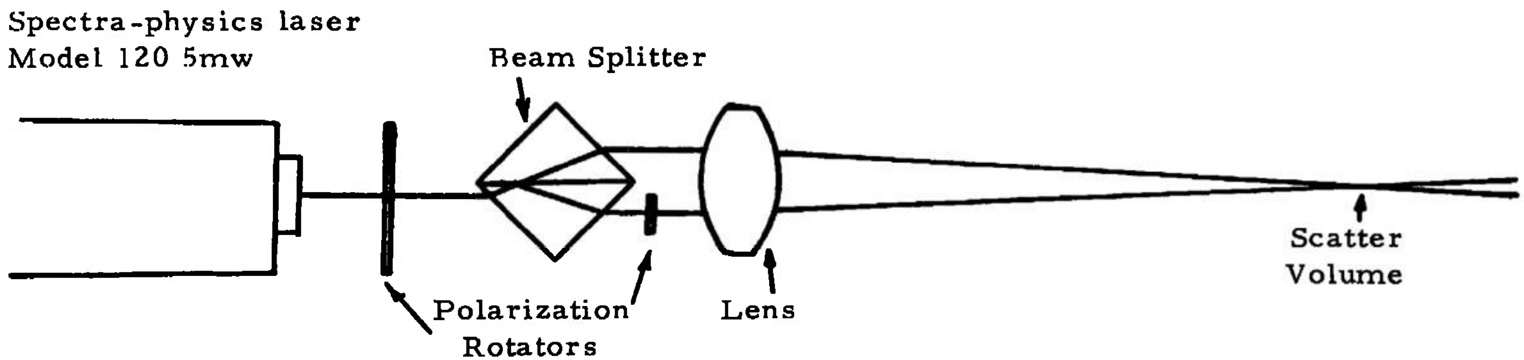

Figure 3: LDV Optics System

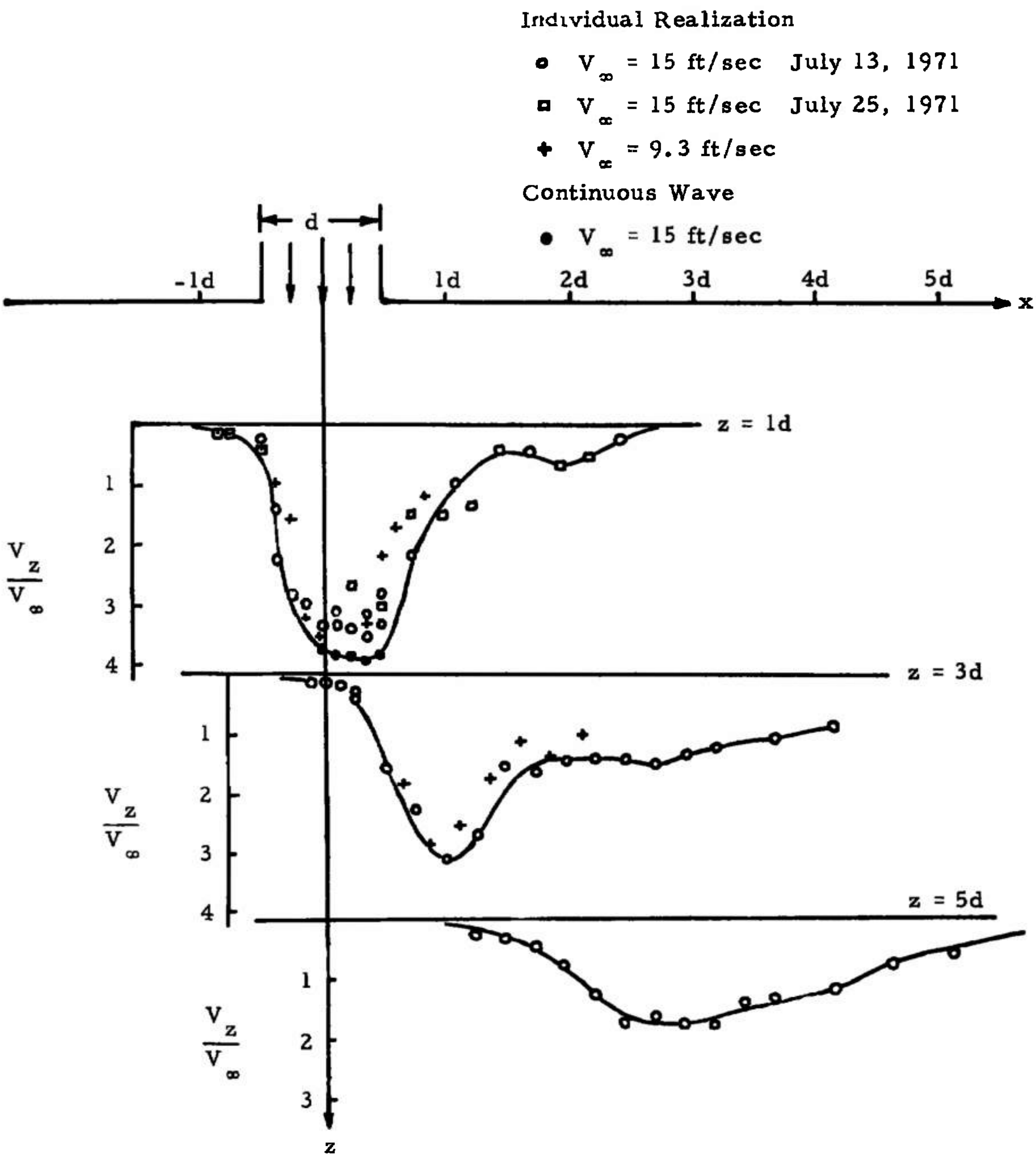

Figure 4: Average Vertical Velocity Components

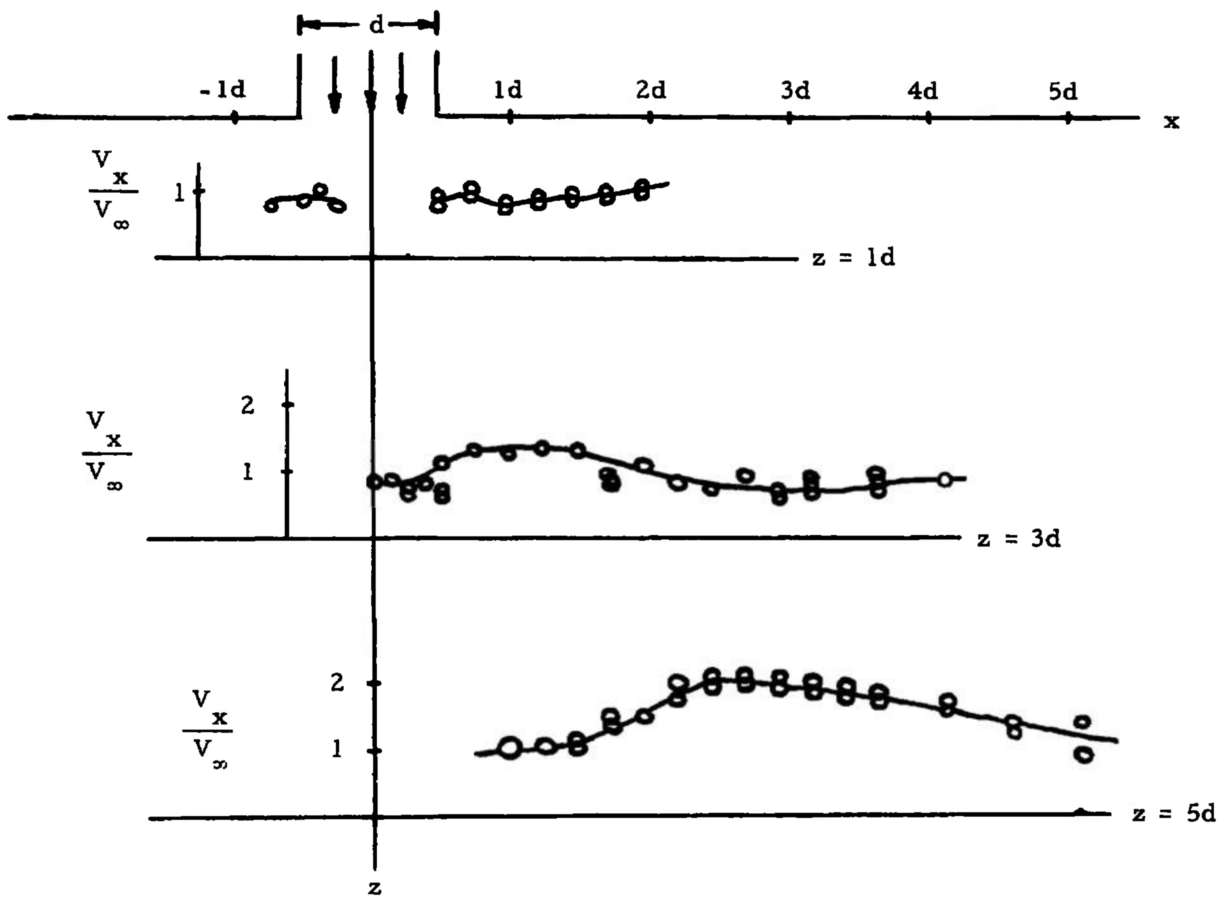

Figure 5: Average Horizontal Velocity Component

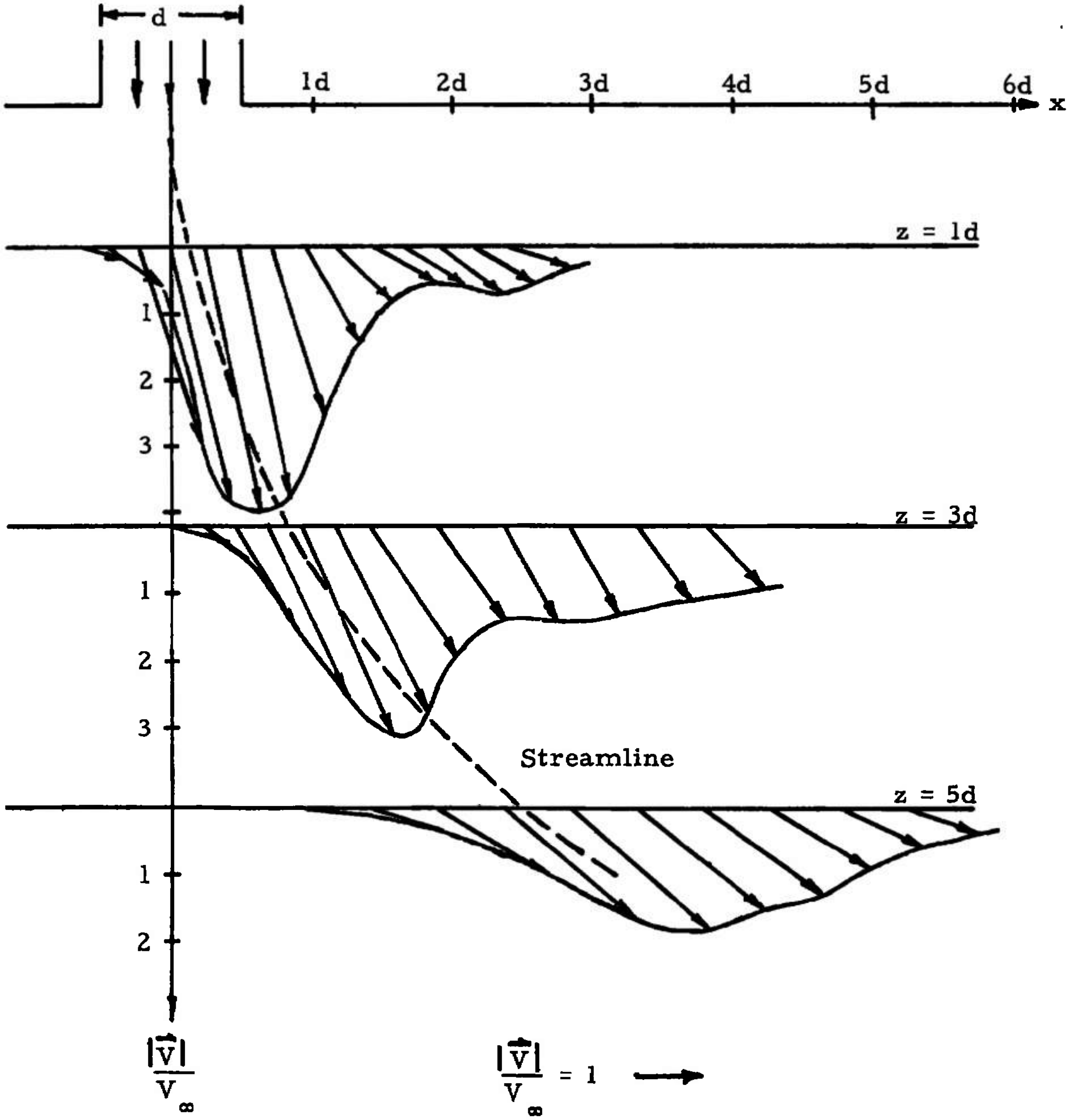

Figure 6: Velocity Magnitude and Flow Direction

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